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EFFECTS OF THERMAL-SHOCK CYCLING ON THIN-FILM CADMIUM SULFIDE SOLAR CELLS

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ABSTRACT

Thermal-shock cycling of Kapton, copper, and molybdenum substrate thin-film cadmium sulfide (CdS) solar cells was conducted in an inert atmosphere by heating the cells to 65° C (338 K) and dipping them into liquid nitrogen. The Kapton substrate cells split in the CdS and delaminated. The open-circuit voltage and fill factor did not change; the short-circuit current and maximum power decreased in direct proportion to the area lost by delamination. The single copper substrate cell tested did not delaminate or degrade after 1352 cycles. The single molybdenum cell tested did not delaminate after 1352 cycles but did degrade; however, comparable molybdenum substrate cells degrade on shelf storage also. The mode of degradation under thermal-shock cycling was different from that observed, by others, under thermal cycling in more realistic earth orbit simulation.

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SUMMARY

Thermal-shock cycling of Kapton, copper, and molybdenum substrate thin-film cadmium sulfide solar cells was conducted by alternately heating the cells between two heater plates and dipping them into liquid nitrogen. The temperature of the cells was maintained at $65^{\circ}\pm1^{\circ}$ C (338 ± 1 K) during the heating portion of the cycle. The thermal-shock cycling was conducted in an inert atmosphere. Photovoltaic performance measurements on the cells were made using a filtered tungsten-iodine light source.

The Kapton substrate cells which underwent thermal-shock cycling split in the cadmium sulfide and delaminated. The substrate side and upper side of the cells after splitting were characterized by matching ridges and valleys, respectively, which corresponded to the current-collecting grid pattern of the cells. Test data on the photovoltaic characteristics of the Kapton substrate cells showed that thermal-shock cycling produced no effect on the open-circuit voltage or fill factor (maximum power divided by the product of the open-circuit voltage and short-circuit current) of the cells. But, there was degradation in the maximum power and short-circuit current of these cells, which could be accounted for by the loss in active cell area resulting from delamination.

However, the Kapton substrate cells that had been thermal-cycled, by others, under more realistic earth orbit simulation (not thermal-shocked) did not delaminate and showed a decrease in fill factor. Therefore, it appears that the mode of degradation of the cells in these thermal-shock cycles is different from that under better simulation.

The one copper and one molybdenum substrate cell that were thermal-shock-cycled did not delaminate. There was no degradation in the current-voltage (I-V) characteristics of the copper substrate cell after 1352 thermal-shock cycles. The molybdenum substrate cell degraded in I-V characteristics. However, what portion of this degradation was due to thermal-shock cycling could not be determined since comparable molybdenum substrate cells degraded on shelf storage.

INTRODUCTION

In certain space missions, such as earth orbiting missions, thin-film cadmium sulfide(CdS)solar cells will be subjected to alternate periods of solar illumination and darkness. The temperature of the cells may reach 65° C (338 K) during solar illumination and -195° C (78 K) in the dark.

As a part of the continuing evaluation program, CdS solar cells are being thermal-cycled under simulated space environmental conditions at various installations (refs. 1 and 2). In these environmental tests, the cells are thermal-cycled in a vacuum chamber (about 10^{-8} torr) whose black walls are cooled with liquid nitrogen. A thermal cycle consists of illuminating the cells for 1 hour with a solar simulator lamp (cell temperature, 65° C) and then intercepting the lamp beam and allowing the cells to cool in the dark for 1/2 hour (cell temperature, -110° C). In these tests the cells degrade in photovoltaic characteristics, and the causes are unknown.

The CdS cells are constructed of several layers of different materials. The thermal coefficients of the various layers could vary by a factor of 5 (ref. 3). This mismatch in thermal coefficients could cause severe stresses to occur within the cells during thermal cycling; these stresses could cause the cells to delaminate and degrade in performance.

Because thermal stress is a possible cause of degradation, a thermal-shock cycling test was devised to exaggerate these effects and thereby, hopefully, to permit accelerated testing of the cells. A series of such thermal-shock-cycling tests were performed to determine the effect of severe thermal stress on cell performance and to see whether these effects are similar to those observed in the more realistic simulated space environment test.

The thermal-shock-cycling test consisted of alternately heating the cells between two heater plates and dipping them into liquid nitrogen (LN_2). The temperature of the cells was maintained at $65^{\circ}\pm1^{\circ}$ C (338 ± 1 K) during the heating portion of the cycle. The thermal-shock cycling was conducted in an inert atmosphere. Photovoltaic performance measurements on the cells were made by using a filtered tungsten-iodine light source. These measurements were made at one sun air mass zero at $25^{\circ}\pm1^{\circ}$ C (298 ± 1 K).

THERMAL-SHOCK-CYCLING APPARATUS

Thermal-shock cycling of the CdS cells was conducted in the thermal cycling apparatus (fig. 1). A timer controlled the pneumatic valve which alternately moved the cells from the heater position into the LN_2-filled dewar. The timer could be set for thermal cycling periods of as much as 2 hours of heat and 2 hours of cold. The heater was made from a parallel arrangement of nichrome wire heater elements. The power dissipated

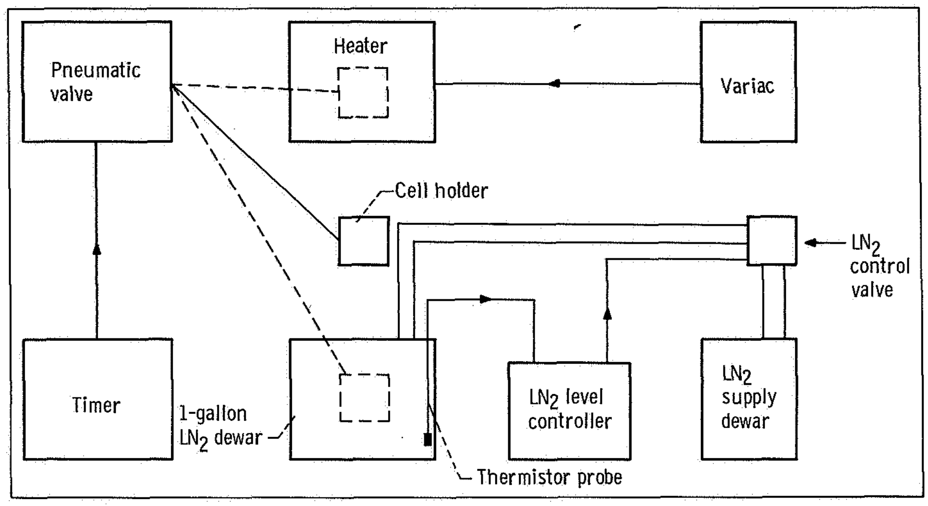


Figure 1. - Schematic of thermal-shock-cycling apparatus.

in the heater elements was controlled by a variac to maintain the desired temperature of the cells.

The 1-gallon LN_2 dewar (fig. 1) was supplied with LN_2 from a supply dewar. The LN_2 level in the 1-gallon dewar was controlled to a set level by a level controller which used a thermistor as a probe. A signal from the thermistor ultimately activated a valve which controlled the flow of LN_2 from the main dewar into the 1-gallon dewar.

The thermal-shock-cycling apparatus was sufficiently automated to allow thermal cycling to be conducted on a 24-hour, 7-day-a-week basis. The thermal cycling apparatus was enclosed, and the LN_2 boil-off provided the cells with an inert atmosphere during cycling.

PHOTOVOLTAIC MEASUREMENT APPARATUS

The light source used to measure the current-voltage (I-V) characteristics of the CdS cells consisted of four 650-watt tungsten-iodine lamps which were operated at a color temperature of 3100 K. The light was filtered through 2 inches (5.08×10^{-2} m) of water to reduce the infrared portion of the light spectrum. The four lights were positioned such that the uniformity over a 4-inch- (10.16×10^{-2}-m-) square area was ±1 percent when measured by a 2-square-centimeter CdS standard.

A constant cell temperature was maintained during the I-V curve measurements by placing the cells on a thermal control block. The cells were kept in good thermal contact with the control block by utilizing a vacuum holddown. The thermal control block was water-cooled, and the temperature was regulated at $25^\circ\pm1^\circ$ C (298±1 K). The intensity of the lamp was adjusted to 140 milliwatts per square centimeter by a standard

CdS cell (2 cm^2) calibrated as described in reference 4. Electrical contact was made to the cells by means of two current and two voltage probes. The I-V curves were measured by using an electronic load, and the cell output was measured on an X-Y recorder.

CELL DESCRIPTION

Three types of CdS solar cells were thermal-shock-cycled in this experiment: Kapton, copper, and molybdenum substrate cells similar in design to those described in references 5 and 6.

The Kapton substrate cells consisted of a Kapton substrate (1 mil (2.54×10^{-5} m) thick) upon which a negative electrode of silver pyre-ml (0.1 to 0.3 mil (2.54×10^{-6} to 7.62×10^{-6} m) thick) was sprayed. A thin layer of zinc was plated onto the silver pyre-ml, and a CdS layer (0.6 to 1 mil (1.52×10^{-5} to 2.54×10^{-5} m) thick) was evaporated onto the zinc. The zinc was used to form an ohmic contact with the CdS. A barrier layer of copper sulfide was then formed on the CdS. A current-collecting gold-plated copper grid was cemented to the barrier layer with a conductive epoxy. A protective Kapton cover (1 mil (2.54×10^{-5} m) thick) was used to encapsulate the cells.

The copper substrate cell consisted of a copper substrate (1 mil (2.54×10^{-5} m) thick) upon which a thin layer of zinc was plated. A layer of CdS (0.6 to 1 mil (1.52×10^{-5} to 2.54×10^{-5} m) thick) was evaporated onto the zinc layer, and then a copper sulfide barrier layer was formed on the CdS. The current-collecting grid and method of grid attachment were the same type as those used for the Kapton substrate cells. A mylar cover (1 mil (2.54×10^{-5} m) thick) was used to encapsulate the cell.

The molybdenum substrate cell consisted of a molybdenum substrate (0.3 to 0.5 mil (7.62×10^{-6} to 1.27×10^{-5} m) thick) upon which was evaporated a layer of CdS (about 1.5 mils (3.81×10^{-5} m) thick). A layer of copper sulfide was formed on the CdS. A current-collecting gold-plated copper grid was attached to the cell by thermal compression bonding. A mylar cover (1 mil (2.54×10^{-5} m) thick) was used to encapsulate the cell.

PROCEDURE

Prior to thermal-shock cycling of the CdS cells, I-V measurements on the cells were made. During the measurements, the temperature of the cells was maintained at $25^{\circ}\pm1^{\circ}$ C (298±1 K), and the intensity at the test plane was 140 milliwatts per square centimeter. The intensity was set with a CdS standard (2 cm^2). The apparatus used for the I-V measurements was described in the section PHOTOVOLTAIC MEASUREMENT APPARATUS.

A copper-constantan thermocouple, coated with a silicon heat-sink compound, was attached to the substrate side of each cell by polyester tape. The cell was then attached to the cell holder by tape applied to the four corners of the substrate side of the cell. The cell holder was attached to the arm on the pneumatic valve.

The 1-gallon dewar (fig. 1) was filled with LN_2. Boil-off from the LN_2 provided a relatively inert atmosphere for the cells during thermal-shock cycling, since the thermal-shock-cycling apparatus was enclosed. The timer which controlled the thermal-shock cycling period was set for the desired cycle time, and the cycling was started. Several heat-cool cycle times were used varying from 60 minutes - 30 minutes to 5 minutes - 5 minutes. The thermal-shock cycling consisted of alternately heating the cells between two heater plates and dipping them into LN_2. The temperature of the cells was maintained at $65^{\circ}\pm1^{\circ}$ C (338±1 K) during the heating portion of the cycle. After a certain number of thermal-shock cycles, the cells were removed from the thermal-shock-cycling apparatus, and I-V measurements on the cells were made. The area of delamination of the cells was also measured. Then, the cells were returned to the thermal-shock-cycling apparatus for additional cycling.

RESULTS AND DISCUSSION

The effects of thermal-shock cycling on Kapton, copper, and molybdenum substrate thin-film CdS solar cells are presented in table I. The data in this table show that the five Kapton substrate cells that underwent thermal-shock cycling split in the CdS and delaminated, whereas the one copper and one molybdenum cell thermal-shock-cycled did not delaminate. (The copper and molybdenum cells are experimental cells and only one of each type was thermal-shock-cycled since a limited quantity of these cells was available at the time the thermal-shock-cycling experiment was conducted.)

A representative Kapton substrate CdS cell (cell 4, table I) that delaminated is shown in figure 2. This cell was cycled for 250 cycles (5 min heat - 5 min LN_2). After cycling, the cell was further delaminated manually by pulling the upper and lower portions apart. The dark portion of the delaminated cell (fig. 2), to the left of the line labeled "tear junction," is the point to which the cell delaminated as a result of thermal-shock cycling. The light portion of the delaminated cell, to the right of the line labeled "tear junction," marks the beginning of the region where the cell was manually delaminated. The manually delaminated portion of the CdS cell did not split in the CdS but pulled away from the substrate, leaving all the CdS on the upper portion of the cell.

A photomicrograph of a cross section of the upper half of the cell at the junction of the thermal and manual delamination is presented in figure 3. On the manually delaminated portion of the cell (on the left), all the CdS stuck to the upper portion of the cell; on the thermally delaminated portion (on the right), the cell split in about the center of

TABLE I. - EFFECTS OF THERMAL-SHOCK CYCLING ON KAPTON, COPPER, AND MOLYBDENUM SUBSTRATE CADMIUM SULFIDE SOLAR CELLS

Cell	Cell construction			Encap-sulating material	Fabrication date	Number of thermal-shock cycles	Heating cycle, 65° C (338 K)	Cooling cycle, -195° C (78 K)	Ratio of values after cycling to initial values					Remarks
	Substrate material and thickness, mil (m)	Grid					Cycle time, min		Maximum power, $P_m/(P_m)_0$	Open-circuit voltage, $V_{oc}/(V_{oc})_0$	Short-circuit current, $I_{sc}/(I_{sc})_0$	Fill factor, FF/FF_0	Active area, A/A_0	
		Material	Method of contact											
1	Kapton, 1 (2.54×10^{-5})	Gold-plated copper	Conductive epoxy	Kapton	Nov. 1967	319	60	30	90	100	90	100	89	Cells split in CdS and delaminated. No change in open-circuit voltage.
2					Nov. 1967	319	60	30	89	100	91	98	90	Change in maximum power and short-circuit current could be accounted for by a loss in cell active area resulting from delamination.
3					Oct. 1967	475	5	5	98	100	98	99	99	
4					Oct. 1967	250	5	5	74	100	74	101	76	
5					March 1967	258	5	5	84	101	84	99	84	
6	Copper 1 (2.54×10^{-5})	Gold-plated copper	Conductive epoxy	Mylar	Dec. 1967	1352	10	5	101	101	99	100	100	Cells did not delaminate. No change in photovoltaic characteristics.
7	Molybdenum, 0.3 to 0.5 $(7.62\times10^{-6}$ to $1.27\times10^{-5})$	Copper	Thermal compression	Mylar	May 1967	1352	10	5	76	98	80	97	100	Cell did not delaminate. Photovoltaic characteristics discussed in RESULTS AND DISCUSSION.

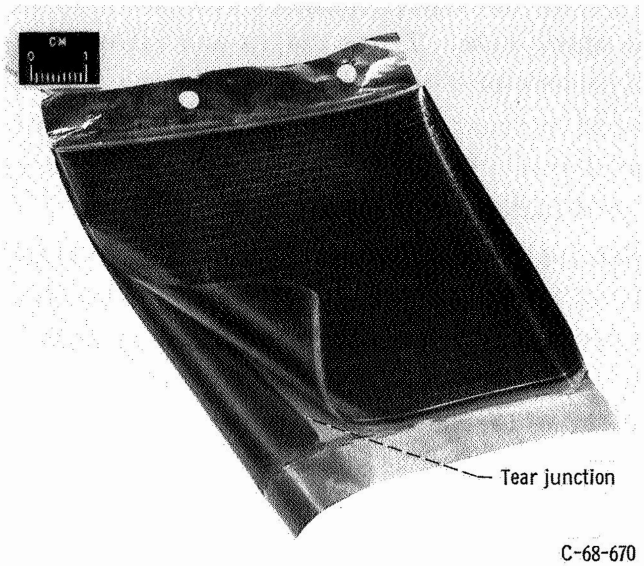


Figure 2. - Effect of thermal-shock cycling on representative Kapton substrate cadmium sulfide solar cell.

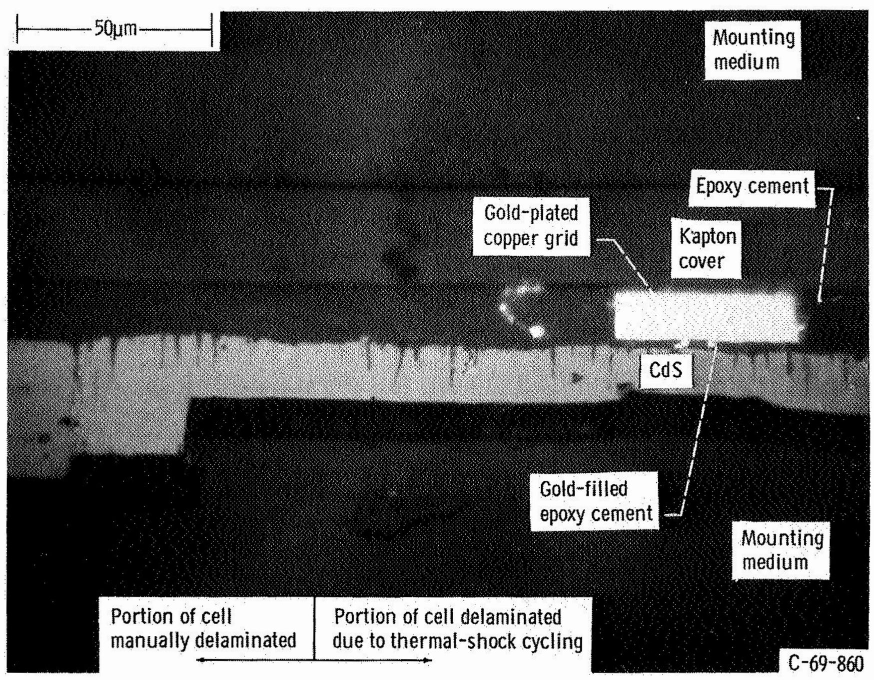


Figure 3. - Photomicrograph of cross section of upper half of delaminated cell shown in figure 2.

the CdS. The substrate side and the upper side of the delaminated cell (fig. 2) are presented in figures 4(a) and (b), respectively. The light used to take the photographs in figure 4 was coming from the left side. Ridges can be seen on the substrate side and matching valleys on the upper side. These ridges and valleys corresponded to the current-collecting grid pattern of the cell. The valleys on the upper portion of the delaminated cell can be seen in cross section in figure 5, a photomicrograph of the upper portion of the delaminated cell. Figure 5 also indicates that the valleys correspond to the current-collecting grid pattern of the cell.

The area of the delaminated regions was computed by a simple process of dividing the regions into component rectangles and triangles. Because the tear junctions were all nearly straight this process was simple and sufficiently accurate.

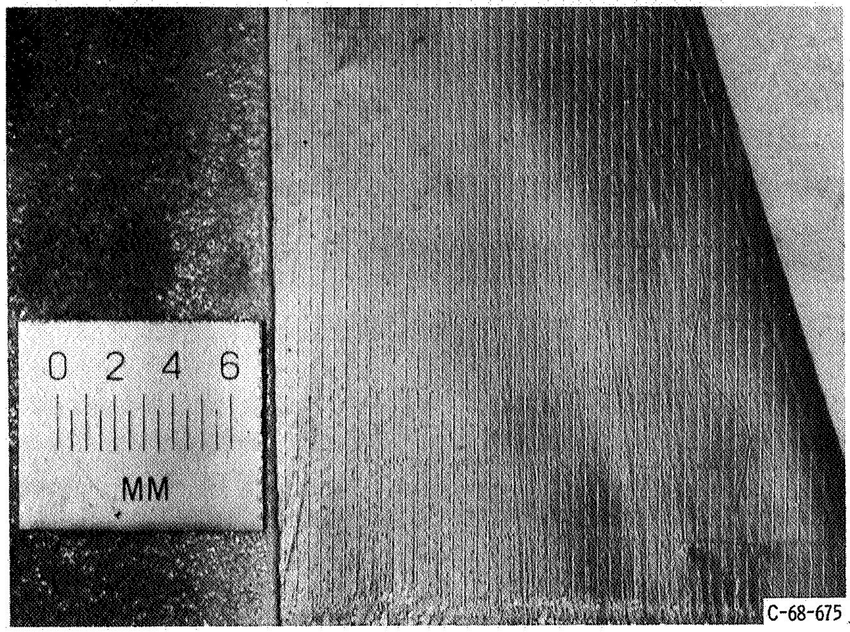
The relative active cell area A/A_0 (relative to cycle zero active cell area) is shown as a function of the number of thermal-shock cycles in figure 6. Only before and after measurements were taken for cells 3, 4, and 5. Intermediate values for cells 1 and 2 show the loss in area was roughly linear with the number of cycles. The rate of area loss was about the same for these two cells, but there was considerable variation in the rate among the other three.

Table I also includes the values after cycling of maximum power P_m, open-circuit voltage V_{oc}, short-circuit current I_{sc}, fill factor FF, and active area A relative to their initial values (indicated by subscript 0). Fill factor is $P_m/(V_{oc} \times I_{sc})$. These data show that thermal-shock cycling produced no degradation in open-circuit voltage or fill factor of the Kapton substrate cells. However, there was degradation in the maximum power and short-circuit current, and it was the same as the loss in active cell area caused by delamination.

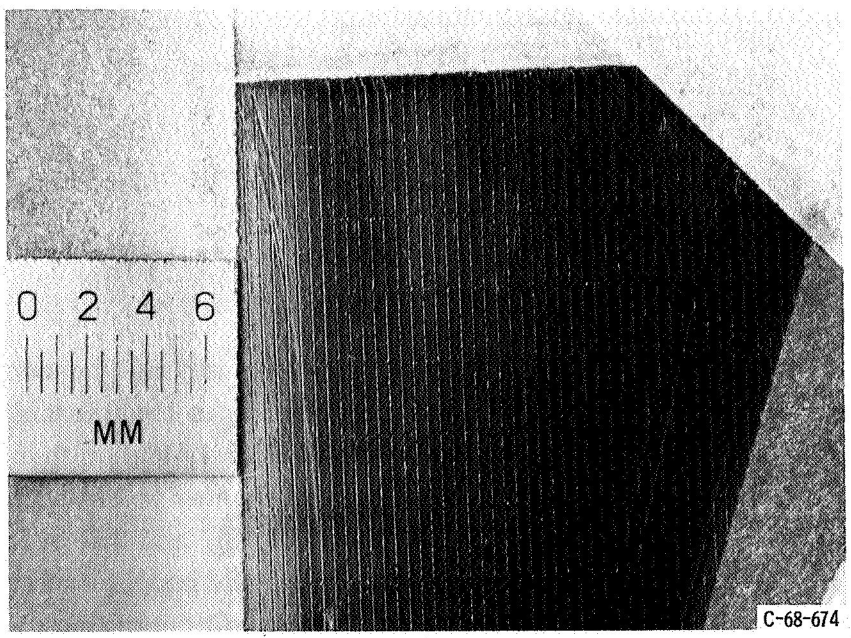
Kapton substrate cells that have been thermal-cycled under more realistic earth orbit simulation (refs. 1 and 2) (not thermal-shocked) did not delaminate and showed a decrease in fill factor. Therefore, it appears that the mode of degradation of the cells subjected to thermal-shock cycling is different from those subjected to earth orbit simulation.

There was no degradation in the I-V characteristics of the copper substrate cell after 1352 thermal-shock cycles. The molybdenum substrate cell degraded in I-V characteristics. However, the portion of degradation due to thermal-shock cycling could not be determined, since molybdenum substrate cells of this vintage also degraded on shelf storage.

The fact that the copper and molybdenum substrate cells did not delaminate is probably due to lower thermal stresses induced in them when undergoing thermal-shock cycling. There are several factors that can yield different stresses (but in the absence of a detailed stress analysis, it is impossible to indicate which factor predominates). The heat-cool thermal-shock cycle times for these cells were different from those for the Kapton cells, but it is unlikely that this is a factor because cycle times for the



(a) Substrate side.



(b) Upper side.

Figure 4. - Delaminated cell shown in figure 2.

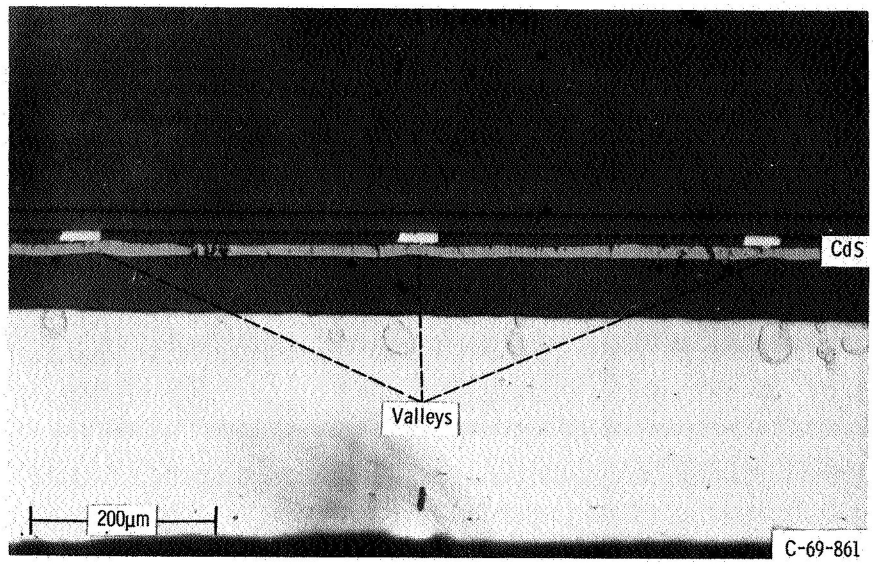


Figure 5. - Photomicrograph of cross section of upper half of delaminated cell shown in figure 2.

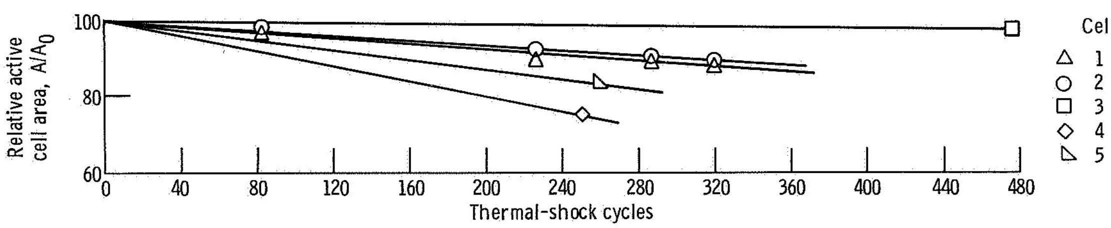


Figure 6. - Effect of thermal-shock cycling on active cell area.

Kapton substrate cells bracketed the values for the copper and molybdenum substrate cells. The thermal conductivity of copper and molybdenum is considerably higher than that of Kapton; however, the thermal conductivity of Kapton is higher than that of mylar. The thermal conductivity of copper is 3.9 watts per centimeter per kelvin, that of molybdenum is 1.4 (ref. 7), that of Kapton is 1.6×10^{-3} (ref. 8), and that of mylar is 3.7×10^{-4} (ref. 9). The possible lower thermal stress in the copper and molybdenum substrate cells could be due to a closer match in the thermal coefficients of expansion of CdS and copper or molybdenum than between CdS and Kapton. The thermal coefficient of expansion of CdS is 4.0×10^{-6} per kelvin, that of copper is 16.8×10^{-6} per kelvin, that of molybdenum is 5.0×10^{-6} per kelvin (ref. 7), and that of Kapton is 20×10^{-6} per kelvin (ref. 8). However, in the absence of a detailed stress analysis, it is impossible to determine which of these factors is predominant.

SUMMARY OF RESULTS

The effects of thermal-shock cycling on Kapton, copper, and molybdenum substrate thin-film CdS solar cells was evaluated, and these effects were compared with the effects of thermal cycling these cells under simulated space environment conditions. The results were as follows:

1. The Kapton substrate cells that were thermal-shock-cycled split in the CdS and delaminated. The substrate side and the upper side of these cells after splitting were characterized by ridges and valleys, respectively, which correspond to the current-collecting grid pattern of the cells. Visual inspection of the Kapton substrate cells that were thermal-cycled under simulated space environmental conditions showed no delamination.

2. There was no degradation in the open-circuit voltage or fill factor (maximum power divided by the product of the open-circuit voltage and short-circuit current) of the Kapton substrate cells which underwent thermal-shock cycling. However, there was degradation in the maximum power and short-circuit current of these cells, which could be accounted for by the loss in active cell area caused by delamination.

3. The mode of degradation of the Kapton substrate cells is different during thermal-shock cycling than during the less severe cycling under simulated earth orbit conditions, in which the cells showed a decrease in fill factor but did not delaminate.

4. The one copper and one molybdenum substrate cell that were thermal-shock-cycled did not delaminate. There was no degradation in the photovoltaic characteristics of the copper substrate cell after it underwent 1352 thermal-shock cycles. The molybdenum substrate cell degraded in photovoltaic characteristics. However, what portion of this degradation was due to thermal-shock cycling could not be determined since molybdenum substrate cells of this vintage degrade on shelf storage.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 5, 1969,
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